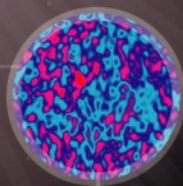
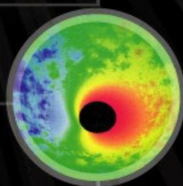
structure and evolution of the universe

BEYOND EINSTEIN:

from the big bang to black holes

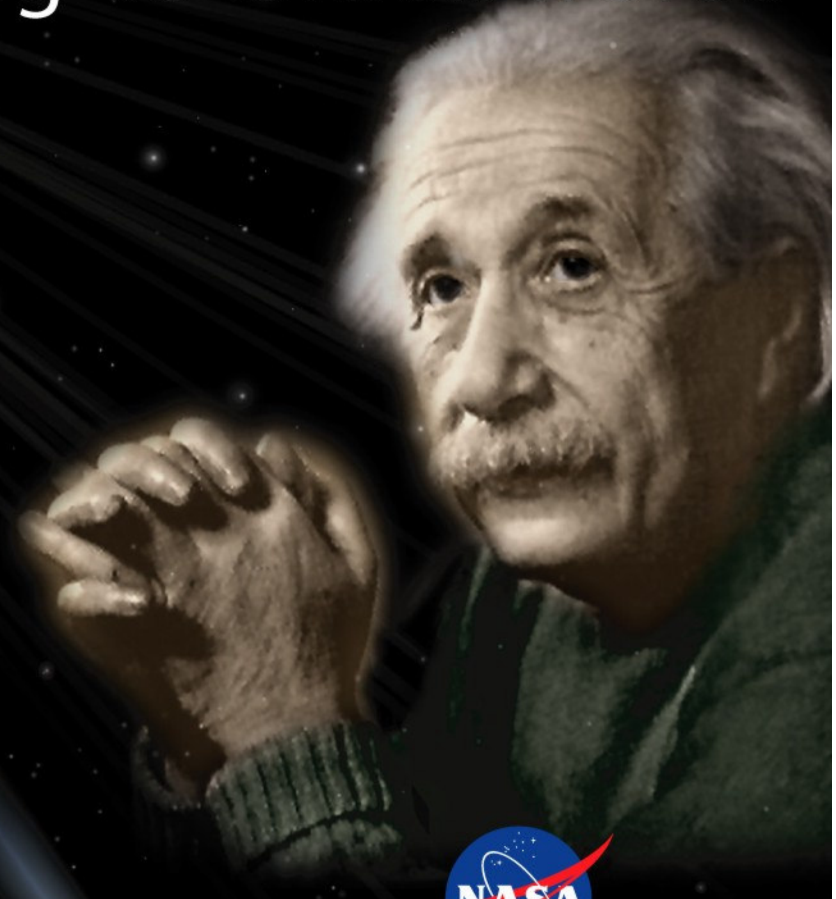


WHAT POWERED THE BIG BANG?

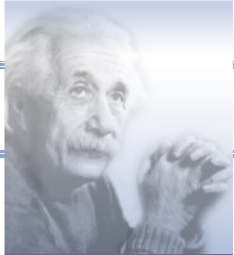


WHAT HAPPENS AT THE EDGE OF A BLACK HOLE?

WHAT IS DARK ENERGY?



National Aeronautics and
Spacetime Administration



SEU 2003 Roadmap

SEUS

Rocky Kolb, Chair (Fermilab)

Joel Bregman (Michigan)

Lynn Cominsky (Sonoma State)

Chuck Dermer (NRL)

Kathy Flanagan (MIT)

Tim Heckman (JHU)

Jackie Hewitt (MIT)

Dan Lester (Texas)

Brad Peterson (Ohio State)

Sterl Phinney (Caltech)

Simon Swordy (Chicago)

Nick White (GSFC)

Ned Wright (UCLA)

Hal Yorke (JPL)

Paul Hertz, Exec Sec (NASA)

Roadmap Team

*Sterl Phinney, Chair (Caltech)

Sean Carroll (Chicago)

Sarah Church (Stanford)

*Kathy Flanagan (MIT)

Roy Gould (CfA)

Craig Hogan (Washington)

Steve Kahn (Columbia)

*Rocky Kolb, SEUS Chair (Fermilab)

*Dan Lester (Texas)

Bob March (Wisconsin)

Mike Shull (Colorado)

*Simon Swordy (Chicago)

*Nick White (GSFC)

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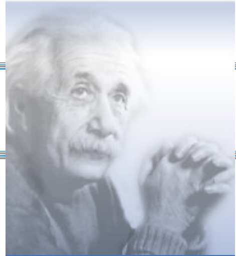
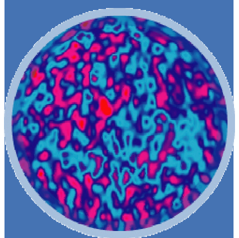
*SEUS members



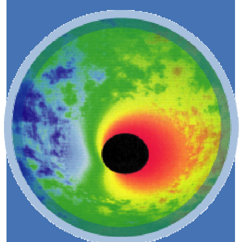
Completing Einstein's Legacy

Einstein's legacy is incomplete, his theory fails to explain the underlying physics of the very phenomena his work predicted



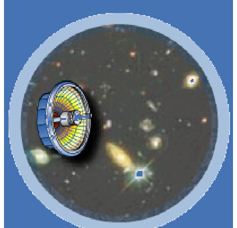
BIG BANG

What powered the Big Bang?



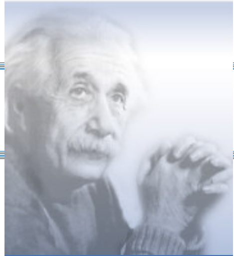
BLACK HOLES

What happens at the edge of a Black Hole?



DARK ENERGY

What is the mysterious Dark Energy pulling the Universe apart?



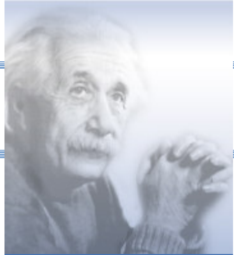
Realizing Science Beyond Einstein

Three inter-linked elements that work together:

1. **<u>Einstein Great Observatories</u> providing breakthrough increases in capabilities to address all Beyond Einstein science:**
   - **LISA: Gravitational waves from merging black holes and the early Universe**
   - **Constellation-X: Spectroscopy close to the event horizon of black holes and place constraints on dark side of the Universe**

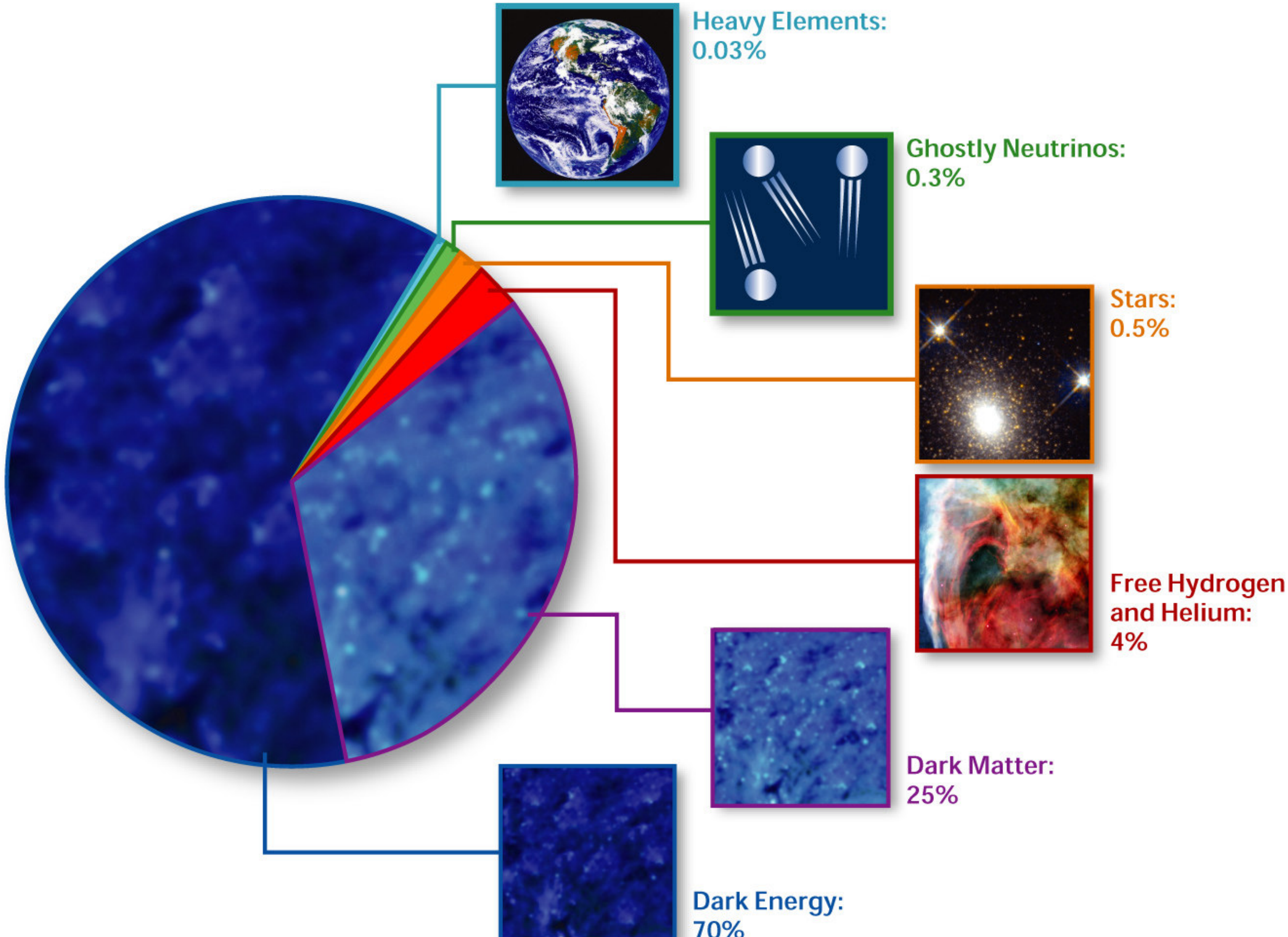
2. **<u>Einstein Probes</u> to address focused science objectives:**
   - **Determine the nature of the Dark Energy**
   - **Search for the signature of inflation in the microwave background**
   - **Take a census of Black Holes of all sizes in the local Universe**

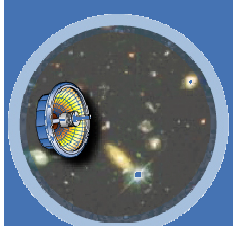
3. **<u>A technology program, theoretical studies and an education program</u> to inspire future generations of scientists and engineers towards the vision:**
   - **Directly detect the gravitational waves emitted during the Big Bang**
   - **Image and resolve the event horizon of a Black Hole**

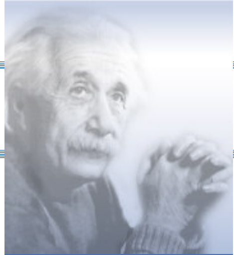


Dark Energy?

We do not know what 95% of the universe is made of!





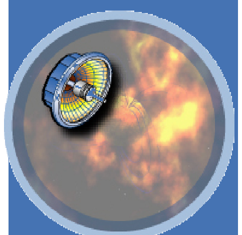


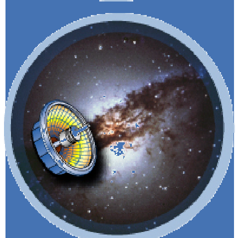
Einstein Probes

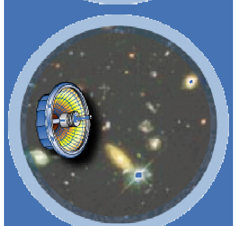
Three focused missions, each designed to address a single high priority science question

- **Priority and science topic determined via NASA strategic planning process, using National Academy recommendations**
  - **Dark Energy Probe**
  - **Inflation Probe**
  - **Black Hole Finder Probe**

- **Competed Principal Investigator missions**
  - **Implementation approach determined by peer review**
  - **Launched every 3-4 years**
  - **$350-500M class missions**







National Research Council Endorsements

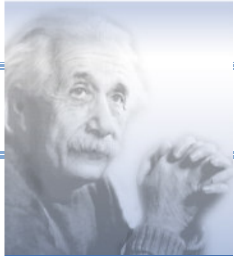
Astronomy & Astrophysics in the New Millennium
2001 Decadal Survey (McKee-Taylor)

Major Initiatives:

1. NGST
2. Constellation-X Observatory
3. Terrestrial Planet Finder
4. Single Aperture Far Infrared Observatory

Moderate Initiatives

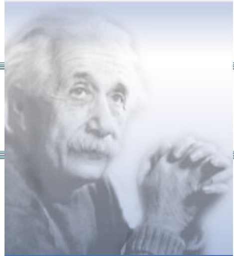
1. Gamma-ray Large Area Space Telescope
2. Laser Interferometer Space Antenna
3. Solar Dynamics Observatory
4. Energetic X-Ray Imaging Survey Telescope
5. Advanced Radio Interferometry Between Space & Earth



National Research Council Endorsements

Connecting Quarks with the Cosmos 2002 (Turner) Not a priority list.

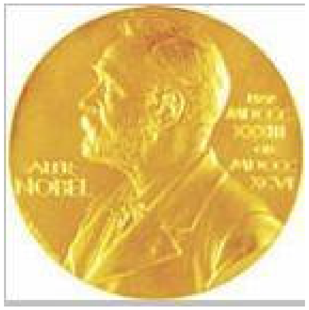
- Measure the polarization of the CMB
- Determine the properties of dark energy
- Use space to probe basic laws of physics (Con-X, LISA)
- (Highest energy cosmic rays)
- (High-energy-density physics)
- (Interagency Initiative)
- (Neutrino masses)



Other Endorsements

Royal Swedish Academy of Sciences
2002 Nobel Prize in Physics

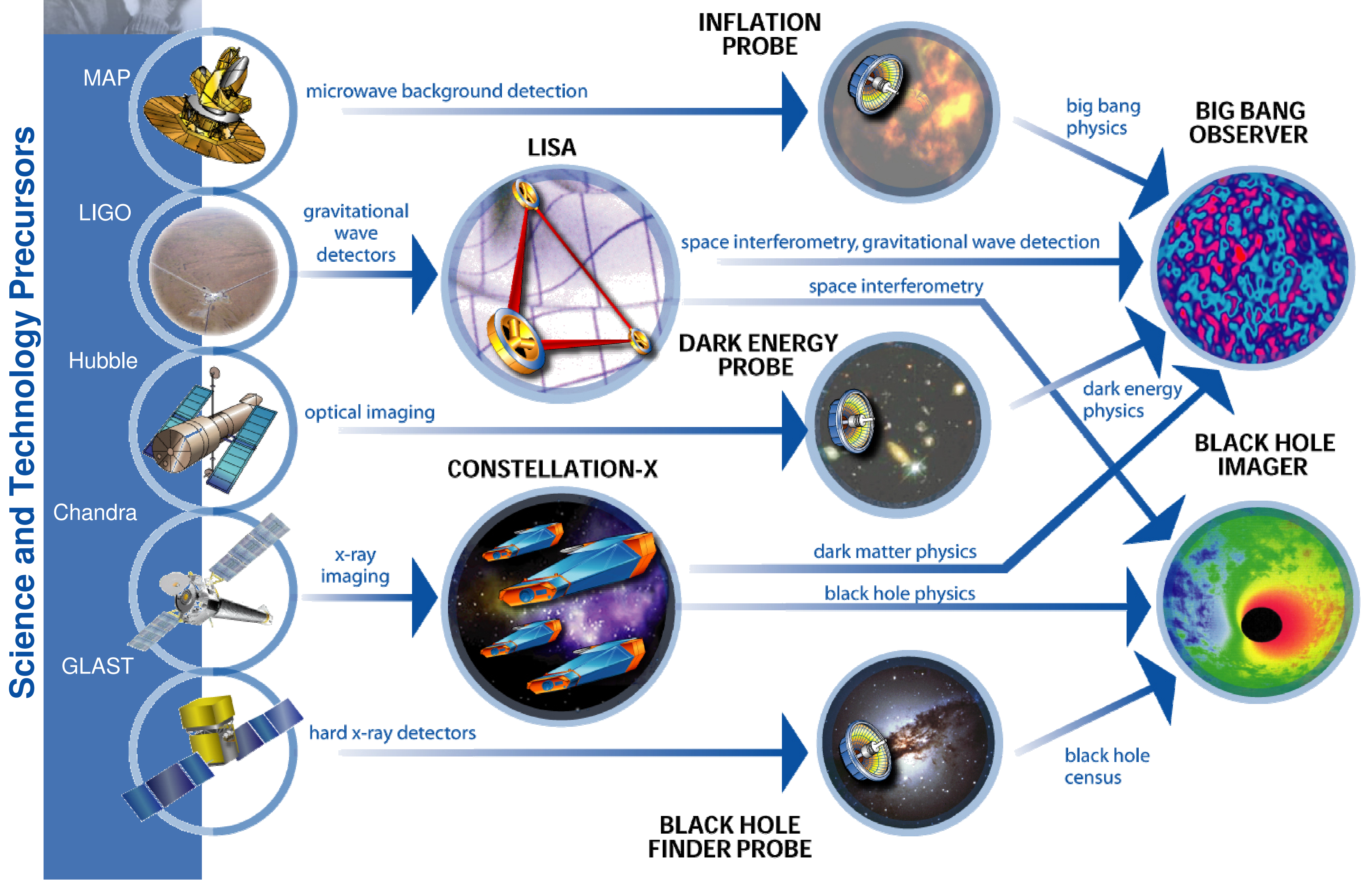
Riccardo Giacconi



"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Hulse & Taylor (1993); Fowler & Chandrasekhar (1983); Penzias & Wilson (1978); Hewish (1974); Hess (1936); Einstein (1921)

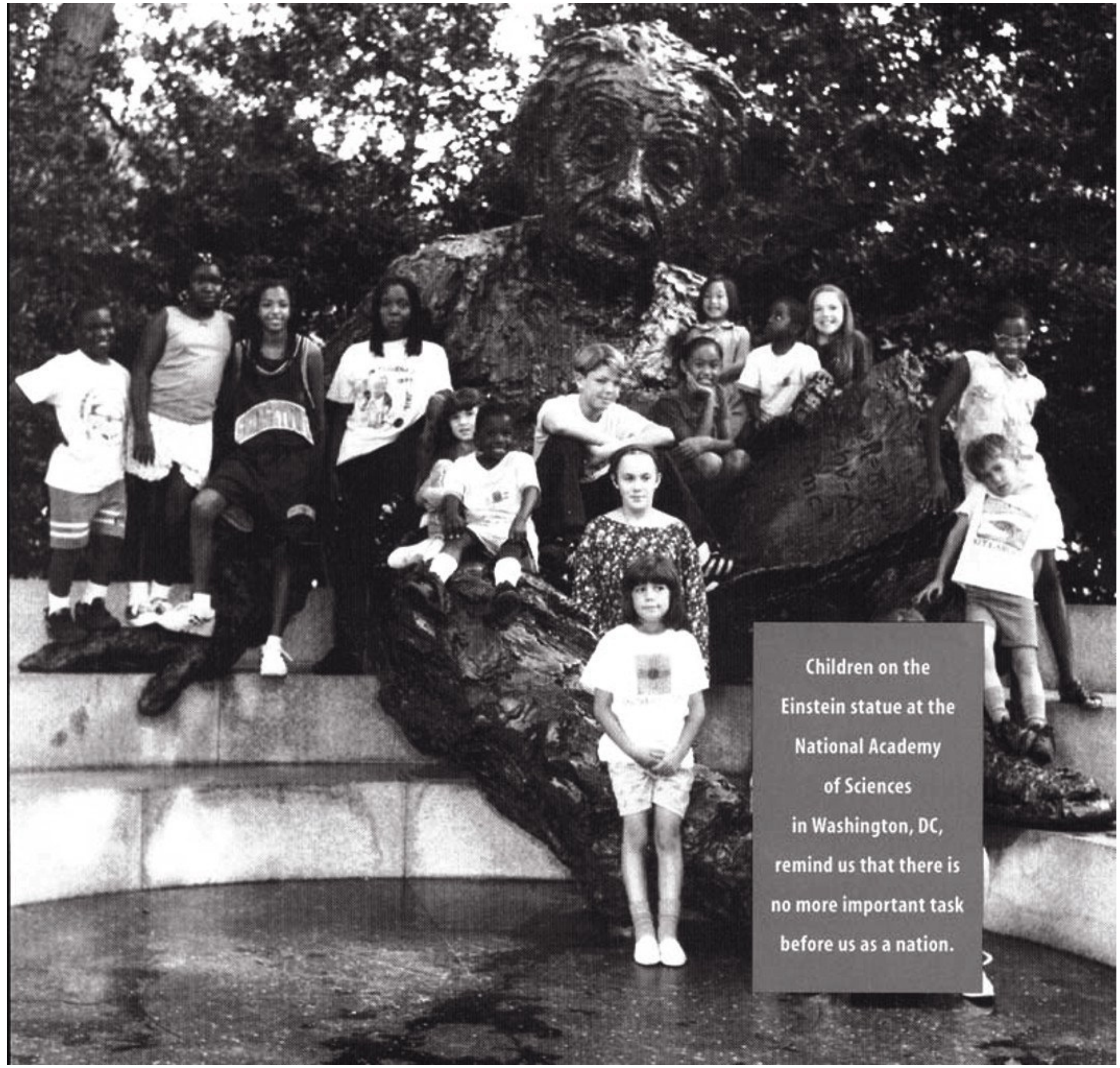
Beyond Einstein Program



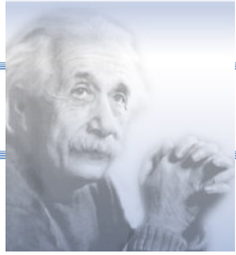
Education and Public Outreach

Big Bang and black holes capture the imagination and can be used to teach physical science at all levels

Beyond Einstein will address the national education priority by inspiring future generations of scientists and engineers, as only NASA can . . .



Children on the Einstein statue at the National Academy of Sciences in Washington, DC, remind us that there is no more important task before us as a nation.

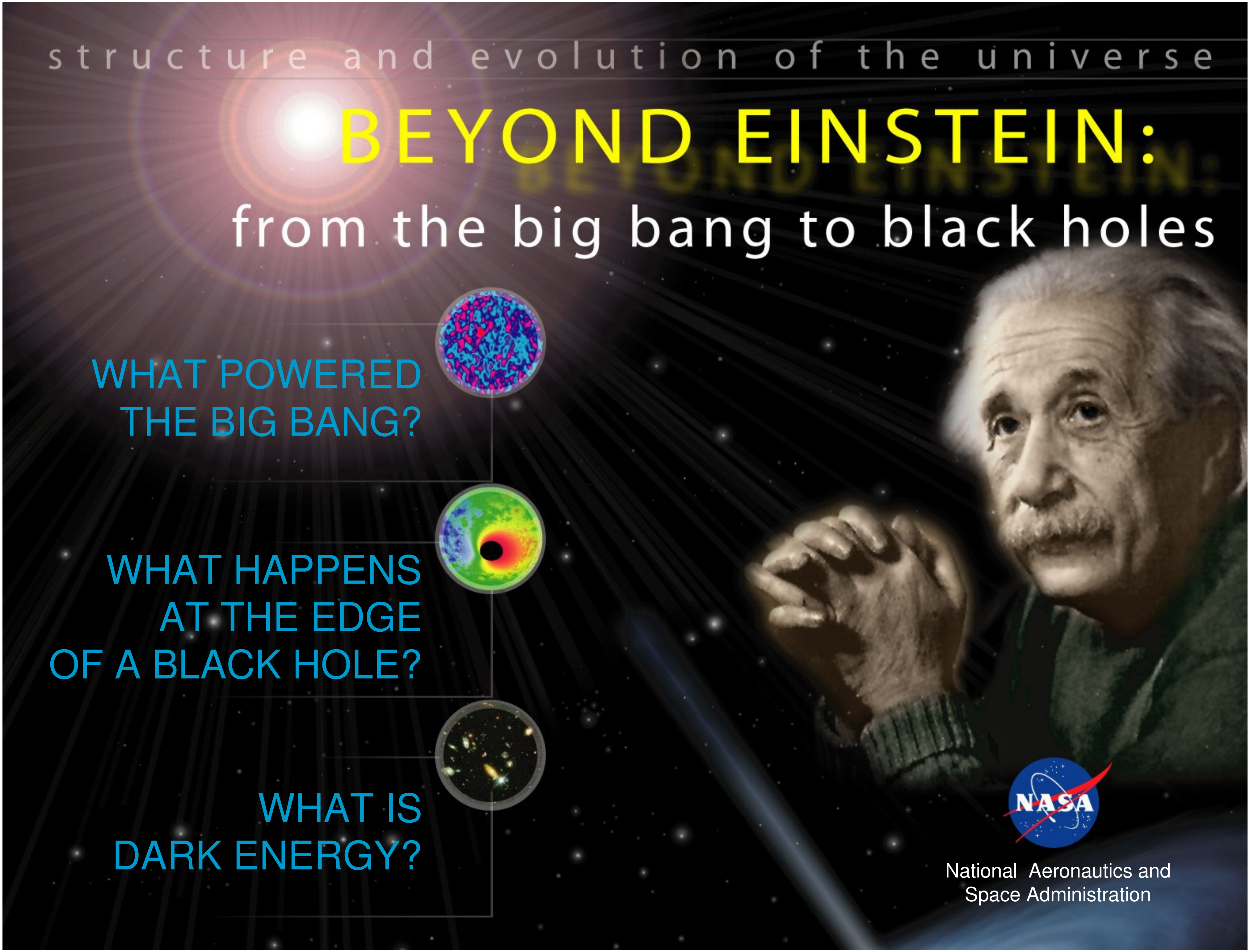


BEYOND EINSTEIN

The 21st Century

How did the Universe begin? Does time have beginning & an end? Does space have edges? The questions are as old as human curiosity. But the answers have always seemed beyond the reach of science. . .

until now!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BEYOND EINSTEIN:
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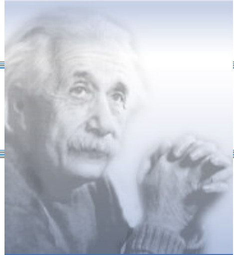
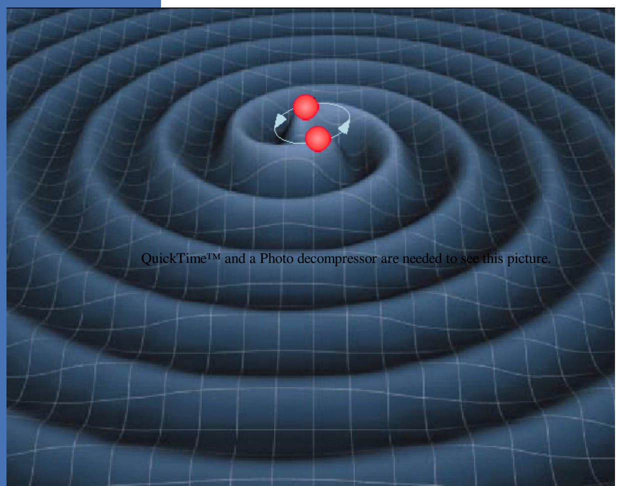
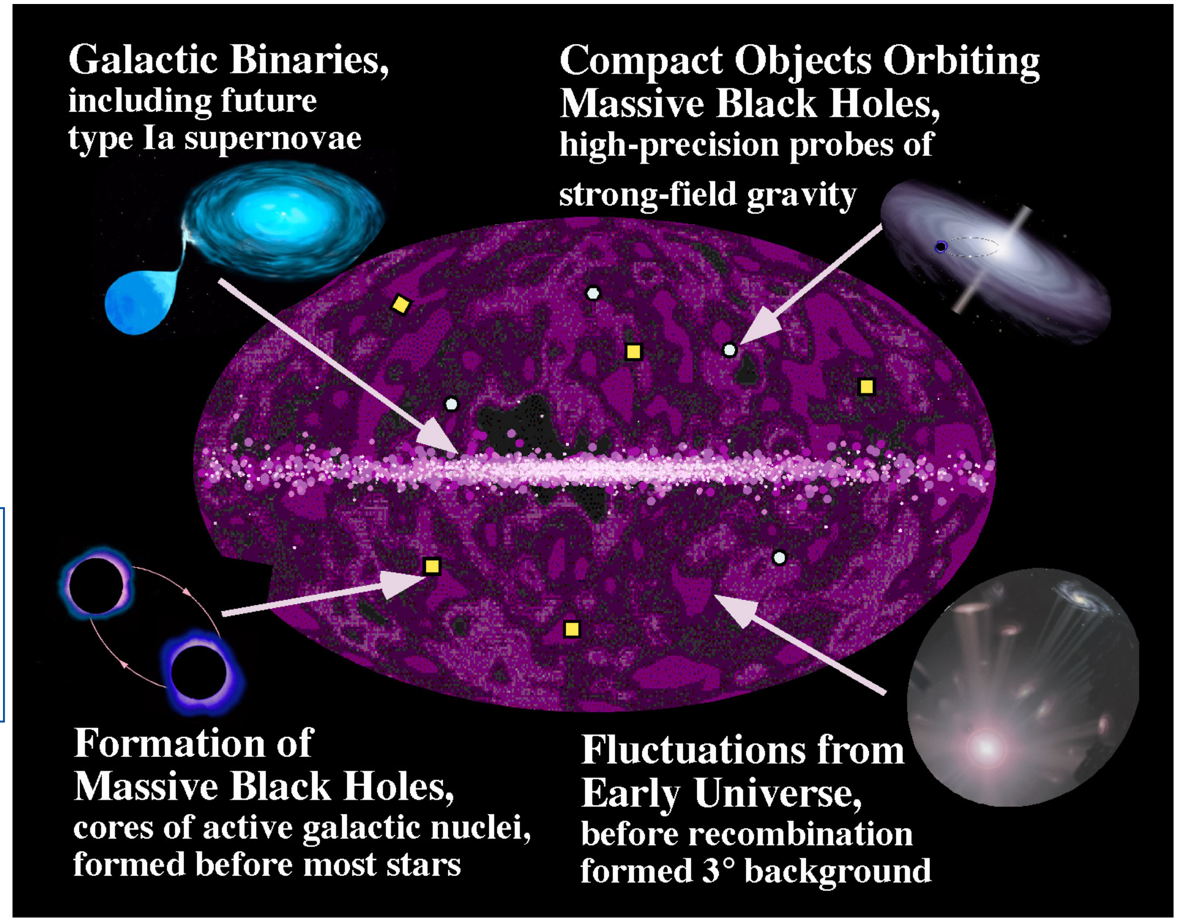
NASA
National Aeronautics and Space Administration



Gravitational Wave Astronomy

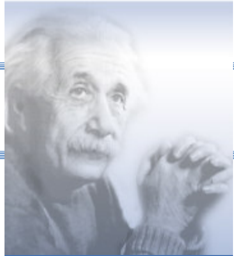
Black holes, neutron stars, and white dwarfs orbiting each other emit gravitational waves





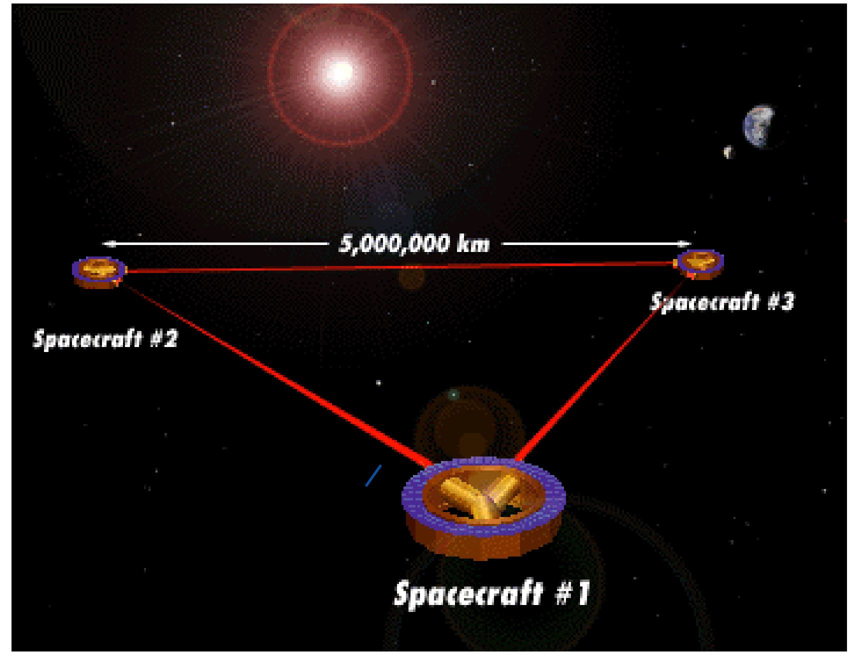
Gravitational radiation from black hole mergers can be used to test General Relativity

The real voyage of discovery consists not in seeing new landscapes, but in having new eyes. - Marcel Proust



Laser Interferometer Space Antenna (LISA)

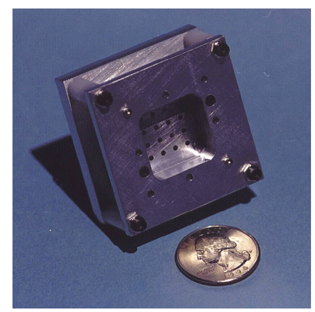
Joint ESA-NASA project



LISA uses a laser based Michelson interferometer to monitor the separation between proof masses in separate spacecraft

- **Three spacecraft separated by 5 million km**
- **Each spacecraft includes two freely falling test masses with drag free operation**
- **Distance changes measured with precision of 4 ppm RMS over 100 seconds**

Flight demonstration of disturbance reduction system ST-7 on ESA SMART-2 mission in 2006



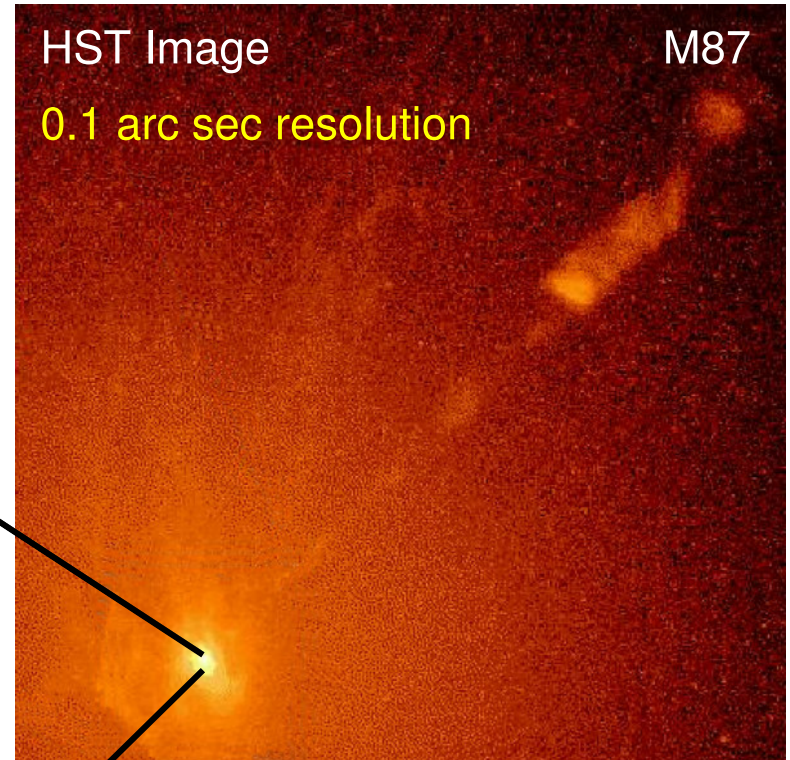
micro-newton thrusters

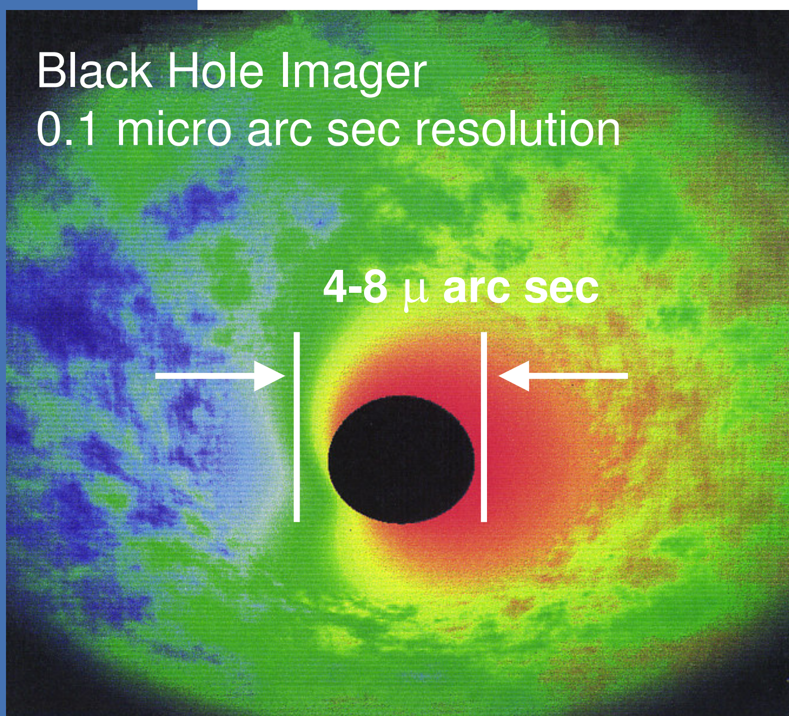
LISA, the first space-based gravitational wave antenna, was given strong endorsement by US National Academy of Sciences McKee-Taylor and Turner Committee Reports

Image a Black Hole!

Hubble, Chandra, and other observatories are showing black holes are common place in the Universe

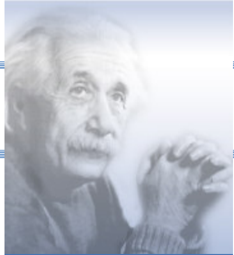
Black holes provide a unique laboratory to test Einstein's theory of gravity





A future black hole imager with a resolution one million times Hubble will observe the effects Einstein predicted

X-ray emission from close to the event horizon provides a powerful probe



Constellation-X

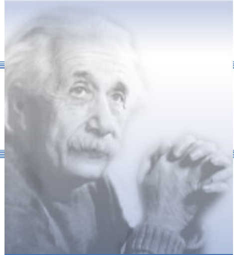
Use X-ray spectroscopy to observe

- Black holes:
  - Probe close to the event horizon
  - Evolution with redshift
- Dark side of the Universe:
  - Clusters of galaxies and large-scale structure
- Production and recycling of the elements:
  - Supernovae and interstellar medium

- 25-100 times sensitivity gain for high resolution spectroscopy in the 0.25 to 10 keV band
- Four satellites at L2 operating as one with advanced X-ray spectrometers

Enable high resolution spectroscopy of faint X-ray sources

**Constellation-X given strong endorsement by
US National Academy of Sciences
McKee-Taylor and Turner Committee Reports**



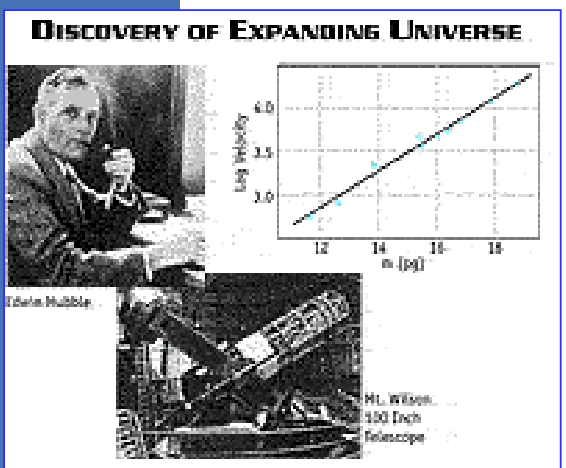
Einstein's Predictions

Three startling predictions of Einstein's relativity:

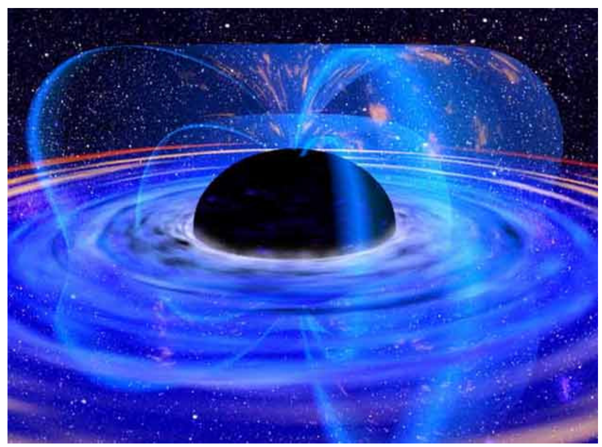
- **The expansion of the Universe (from a big bang)**
- **Black holes**
- **Dark energy acting against the pull of gravity**

Observations confirm these predictions . . .

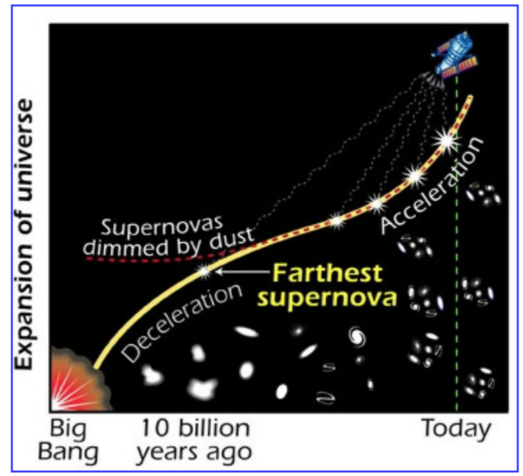
. . . the last only four years ago



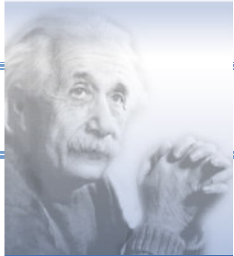
Hubble discovered the expanding Universe in 1929



Black holes found in our Galaxy and at the center of quasars over the past three decades

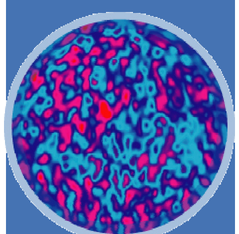


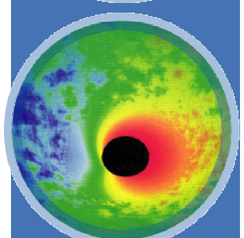
Evidence for an accelerating Universe was observed in 1998

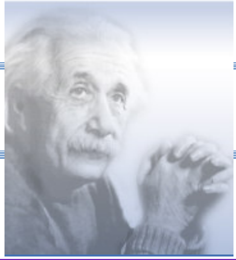


Key features of Beyond Einstein

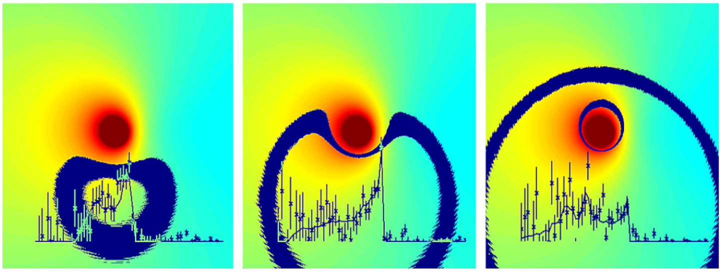
- All missions endorsed by the National Academy of Sciences as high priorities
- Leverage overlapping interest with NSF and DOE programs for collaborative opportunities
- International participation
- Maximally competed acquisition strategy
- Strong linkage to education program and technology







Constellation-X Science Highlights

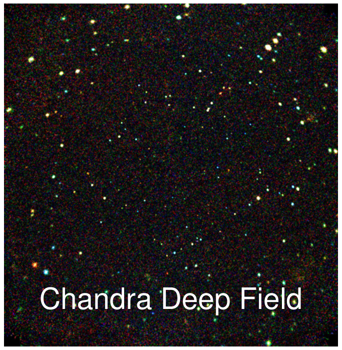


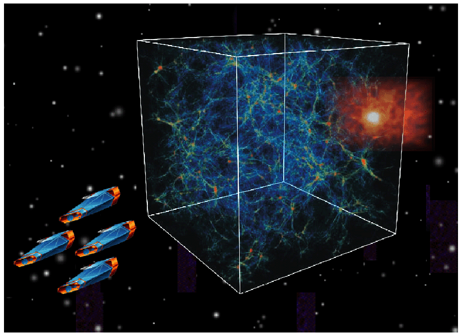
Observe the effects of General Relativity near black hole event horizons

Probe 100,000 times closer to black hole event horizon than at longer wavelengths

Study the evolution and origin of black holes

Obtain detailed spectra to determine evolution and accretion processes

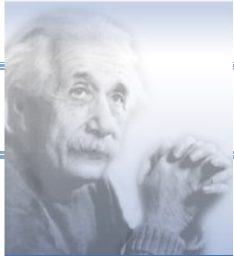




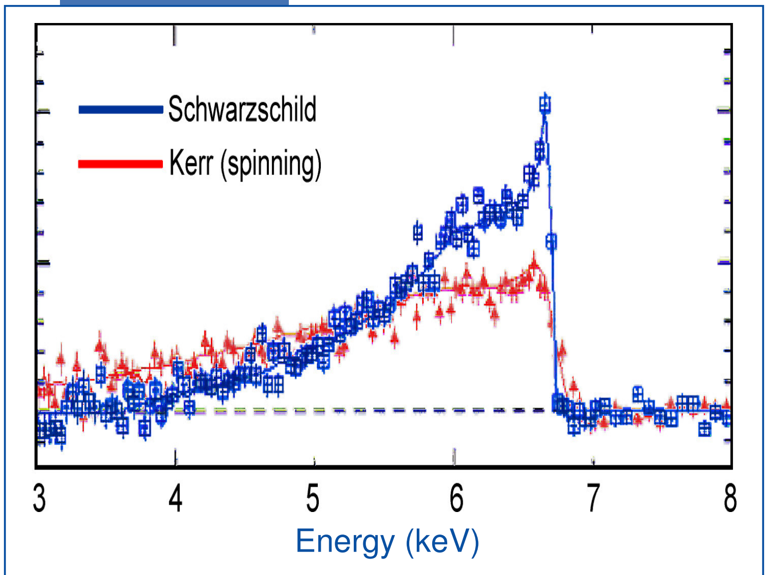
Map formation and evolution of dark matter structures throughout the Universe

Observe the first clusters of galaxies to constrain cosmological models and parameters

Detect missing baryons in the hot Inter Galactic Medium



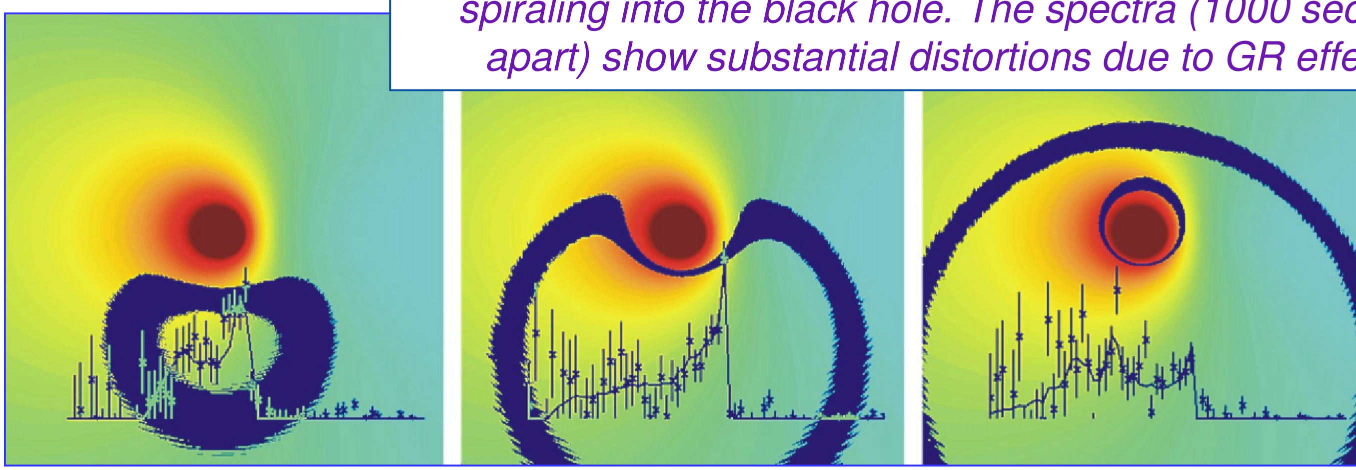
Black Holes and Strong Gravity



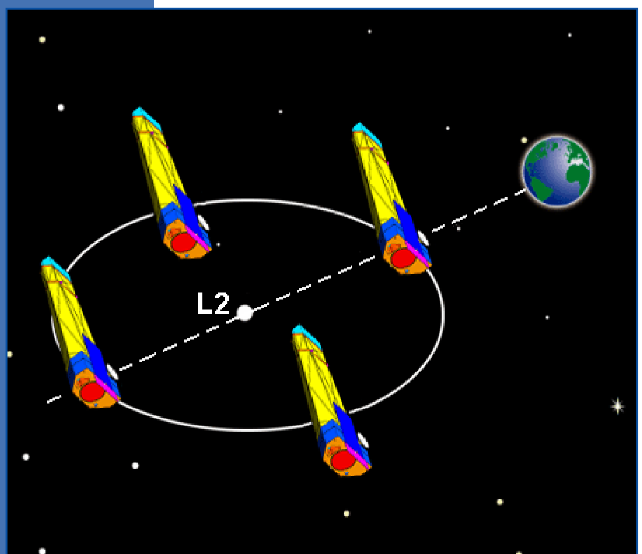
Constellation-X will probe close to the event horizon with 100 times better sensitivity than before

- Observe iron profile from close to the event horizon where strong gravity effects of General Relativity are seen
- Investigate evolution of black hole properties by determining spin and mass over a wide range of luminosity and redshift

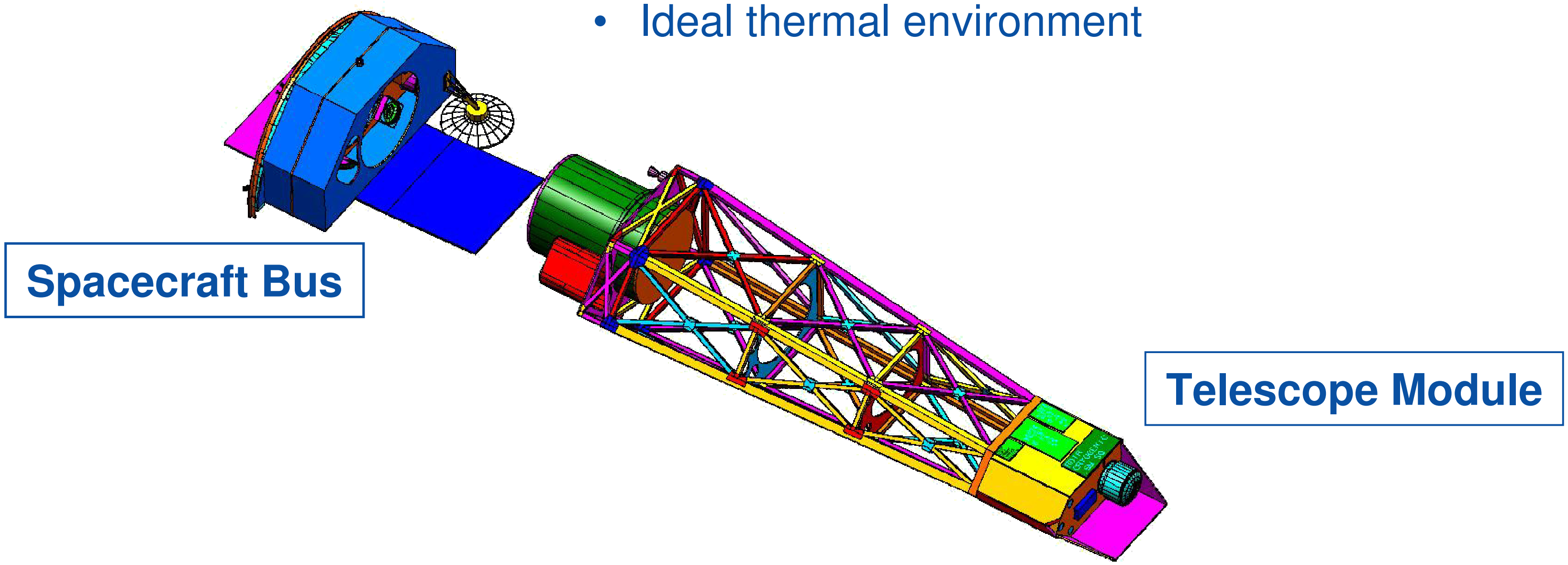
Simulated images of the region close to the event horizon illustrate the wavefront of a flare erupting above material spiraling into the black hole. The spectra (1000 seconds apart) show substantial distortions due to GR effects.

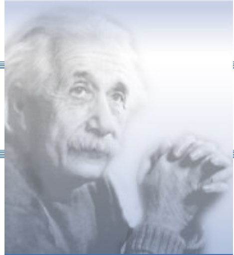


Constellation-X Mission Concept

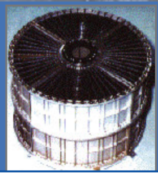


- A multiple satellite approach:
  - A constellation of multiple identical satellites
  - Each satellite carries a portion of the total effective area
  - Reduces risk from any unexpected failure
  - Modular “production line”
- Deep space (L2) orbit allows:
  - High observing efficiency
  - Simultaneous viewing
  - Ideal thermal environment

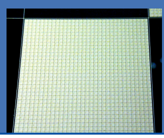




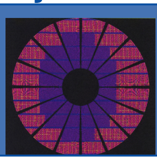
Constellation-X Heritage



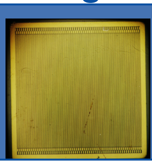
X-ray Mirrors



Micro-calorimeters & cryocoolers



Grating/CCD



Hard X-ray Telescope

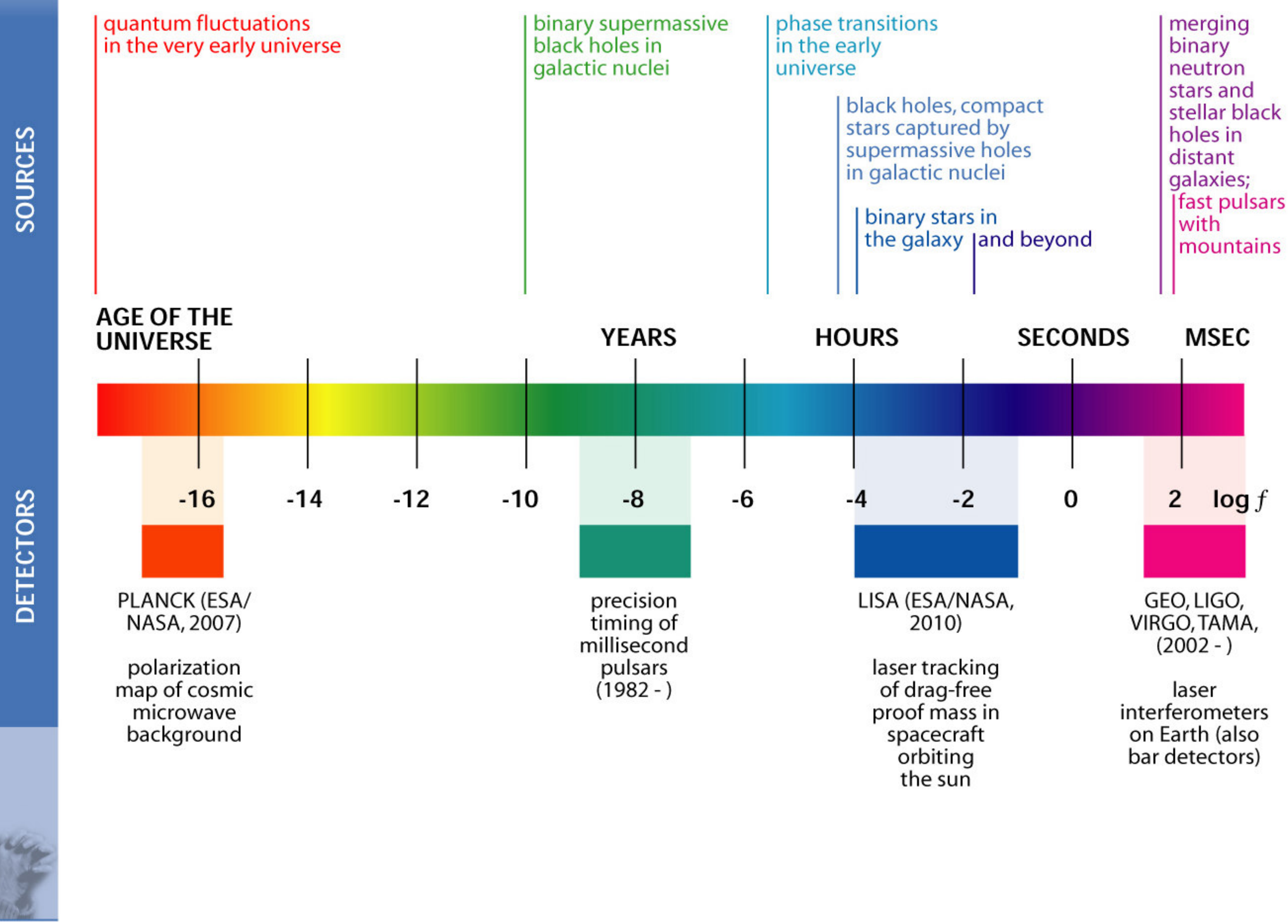
History

- 1995 to 1997 - Mission selected in new mission concepts competition, enters mission formulation with facility science team. Technology roadmap developed.
- 1998 to 2000 - Competition for technology development. GSFC, TRW, and Ball mission architecture studies
- 2000 to 2002 - Constellation-X receives strong endorsement from the NAS Astronomy and Astrophysics 2000-2010 survey and the Committee on the Physics of the Universe

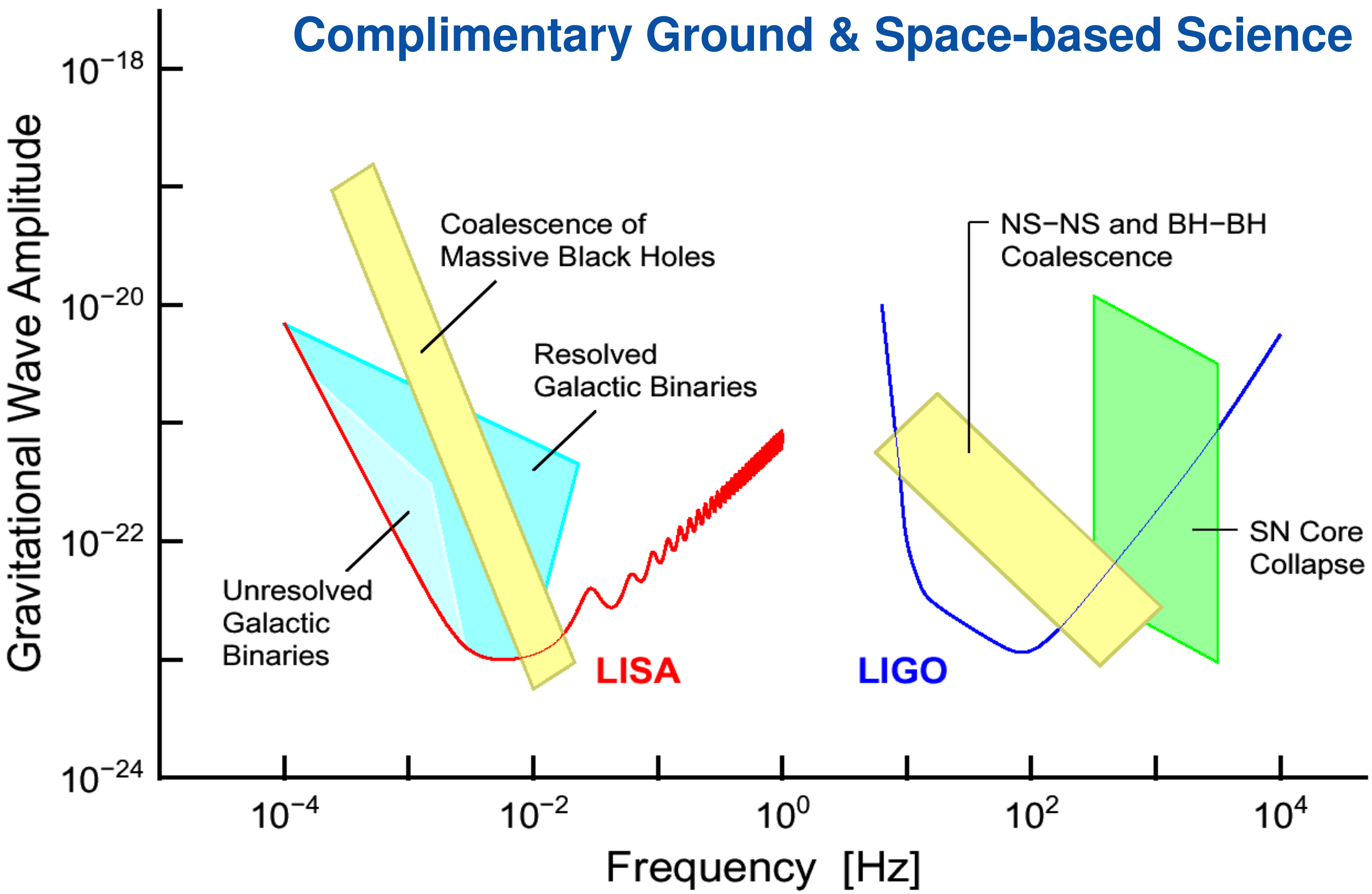
Current Status

- Constellation-X in formulation now for five years - implementation approach is well understood
- Mission extends existing technologies and technology development is well in hand, with substantial progress in all areas.
- Focused technology funding continuing towards critical milestones given OMB

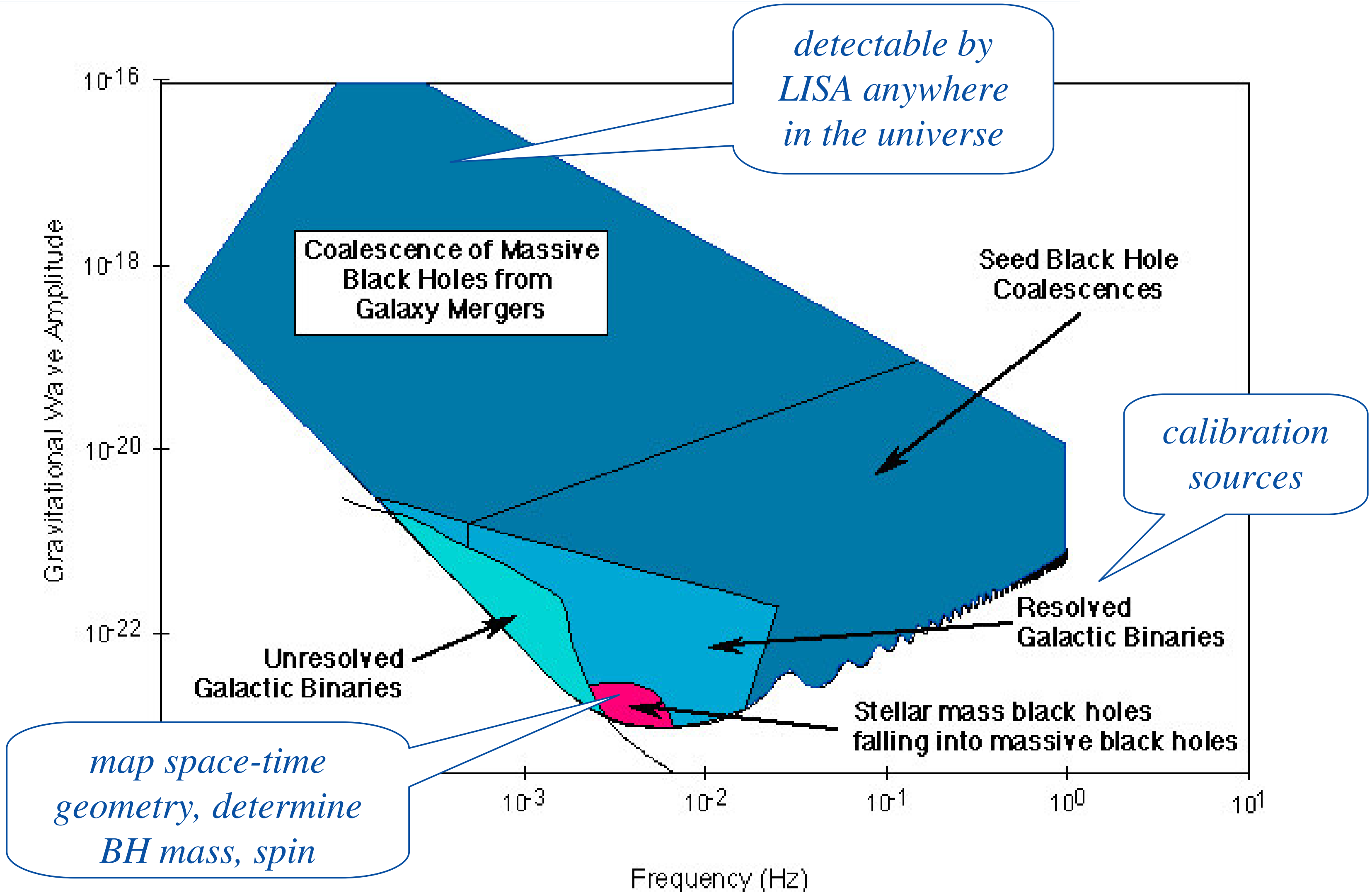
LISA


SOURCES
DETECTORS
quantum fluctuations in the very early universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
-16
-14
-12
-10
-8
-6
-4
-2
0
2
log f
PLANCK (ESA/ NASA, 2007)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
GEO, LIGO, VIRGO, TAMA, (2002 -)
laser interferometers on Earth (also bar detectors)

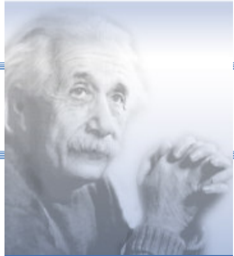
LISA & LIGO Comparison



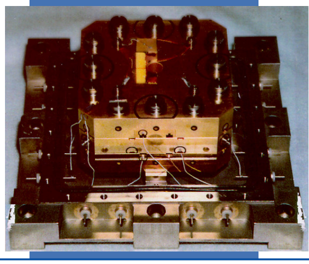
LISA Sensitivity



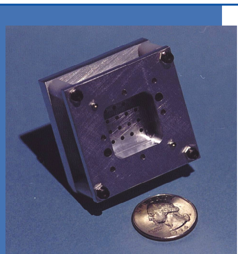
A prime science goal of LISA is the detection of gravitational waves from the coalescence of massive black holes



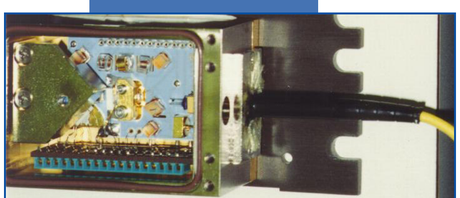
LISA History and Status



Inertial Sensor



Micronewton Thrusters



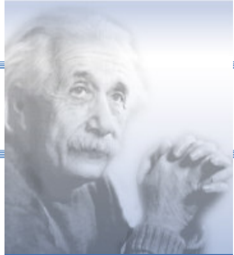
Ultra Stable Laser

History

- 1981 to 1985 - Concept discussed in US
- 1993 to 1997 - Mission configuration studies by ESA and NASA
- 1999/2000 - ESA Industrial Study. ESA selects LISA to be carried out jointly with NASA. LISA enters NASA mission formulation process
- 2000 to 2002 - LISA receives strong endorsement from the NAS Astronomy and Astrophysics 2000-2010 survey and the Committee on the Physics of the Universe
- 2002 - NASA and ESA approve flight demonstration of disturbance reduction system

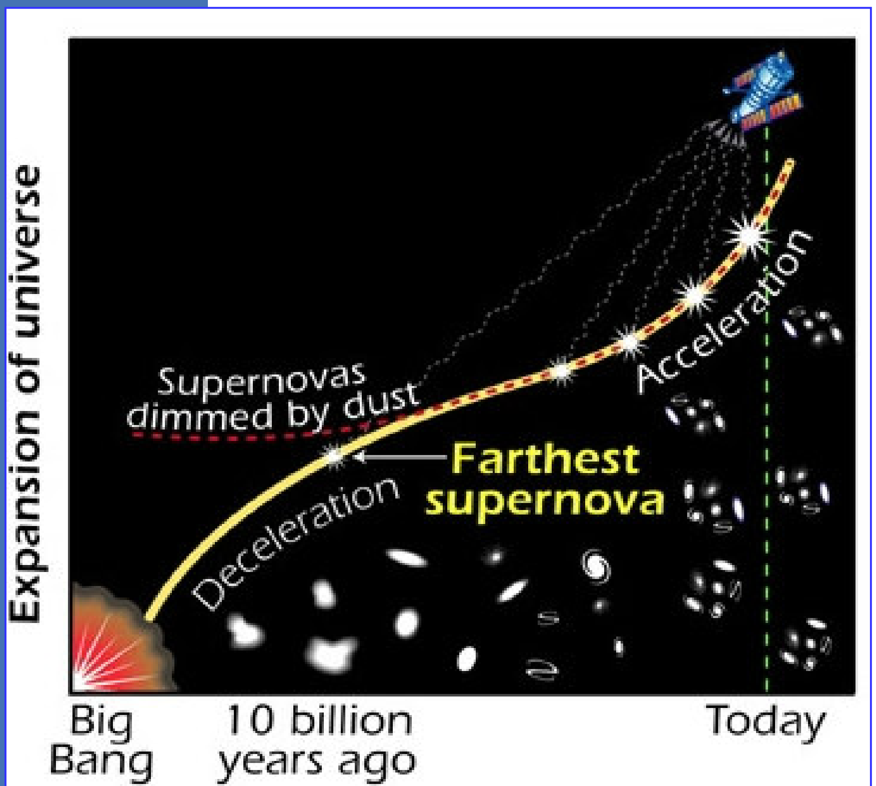
Current Status

- ESA/NASA joint flight demonstration in development
- Technology plan in preparation
- ESA and NASA formulating mission concept

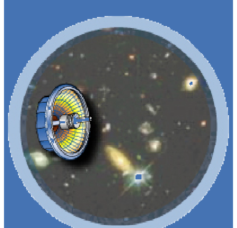


Dark Energy Probe

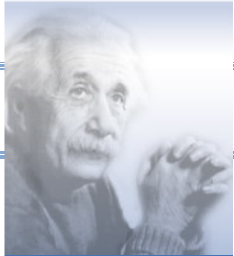
The Einstein Dark Energy Probe will accurately determine the amount of Dark Energy and search for time variations in the energy density with cosmic time



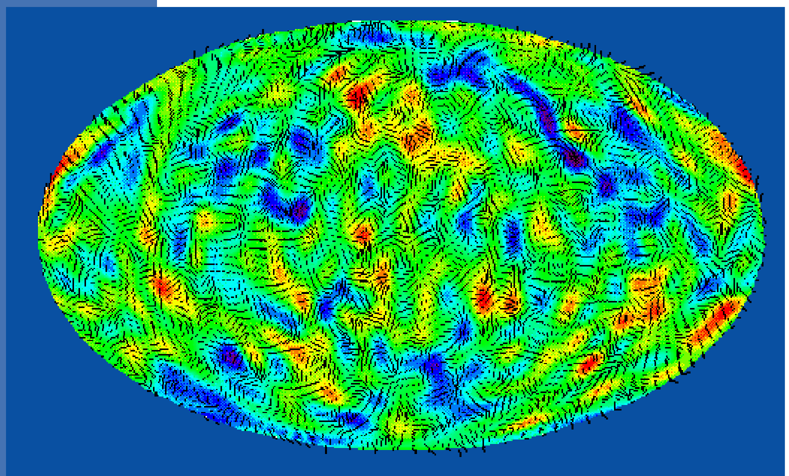
Requires precision observations over the redshift range 0.5 to 2 to observe accurately the acceleration of the Universe



Space based mission using type Ia supernovae as standard candles (SNAP) recommendation by National Academy of Sciences Turner Committee on the Physics of the Universe



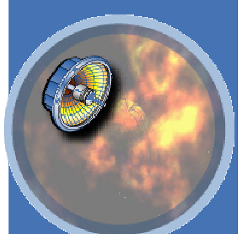
Inflation Probe



Gravitational waves from the period of inflation should be imprinted on the cosmic microwave background in the form of circular polarization

The Einstein Inflation Probe will detect these imprints to provide first indirect detection of gravitational waves from the Big Bang, confirm, and constrain inflation models

Important precursor to Big Bang Observer

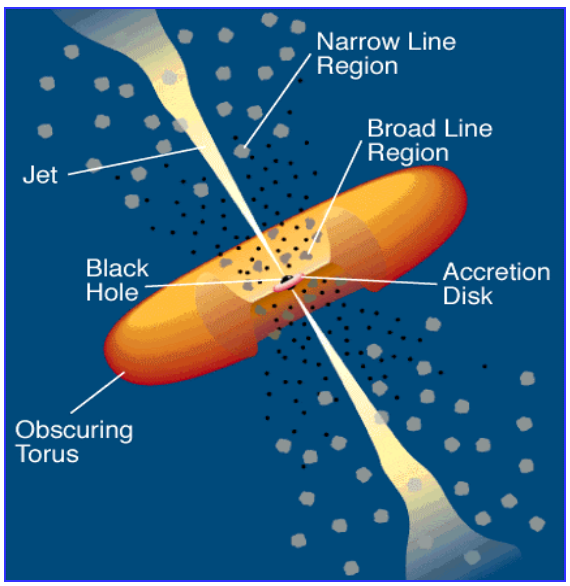


Inflation Probe recommended by US National Academy of Sciences Turner Committee on the Physics of the Universe

Black Hole Finder Probe

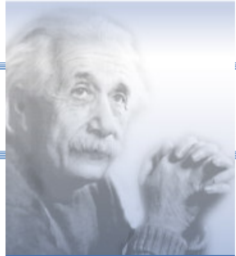
Perform first all sky survey census of black holes of all sizes:

- Find tens of thousands of “optically hidden” black holes buried at the center of nearby galaxies
- A census of the active black holes in our Galaxy

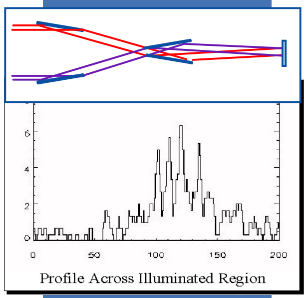


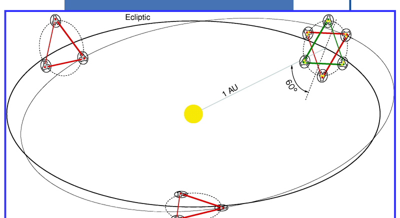
Follow up studies by Constellation-X and eventually the Black Hole Imager will determine black hole spin and mass

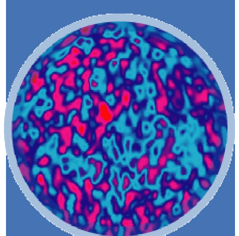
Hard X-ray survey mission (EXIST) endorsed by National Academy of Sciences McKee-Taylor Survey

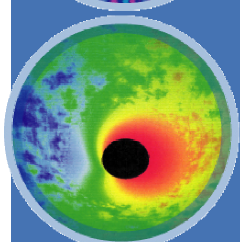


Technology Program





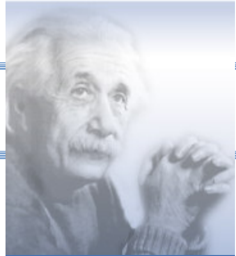




- Forward looking technology and theory program to enable future decisions on the feasibility of the vision missions

- Black Hole Imager
  - Requires 1-10 million times Chandra capability
  - Most promising approach is X-ray interferometry
  - Baselines of 100 to 1,000 m
  - Recent demonstration of X-ray fringes proves feasibility of the basic approach
  - Requires micron station-keeping between optics

- Big Bang Observer
  - Four LISA-type interferometers distributed around solar system
  - S/C separation 50,000 km (100x smaller than LISA)
  - Peak sensitivity near 0.1 Hz
  - Strain sensitivity 1000x better than LISA
  - Inertial sensor 10x better than LISA

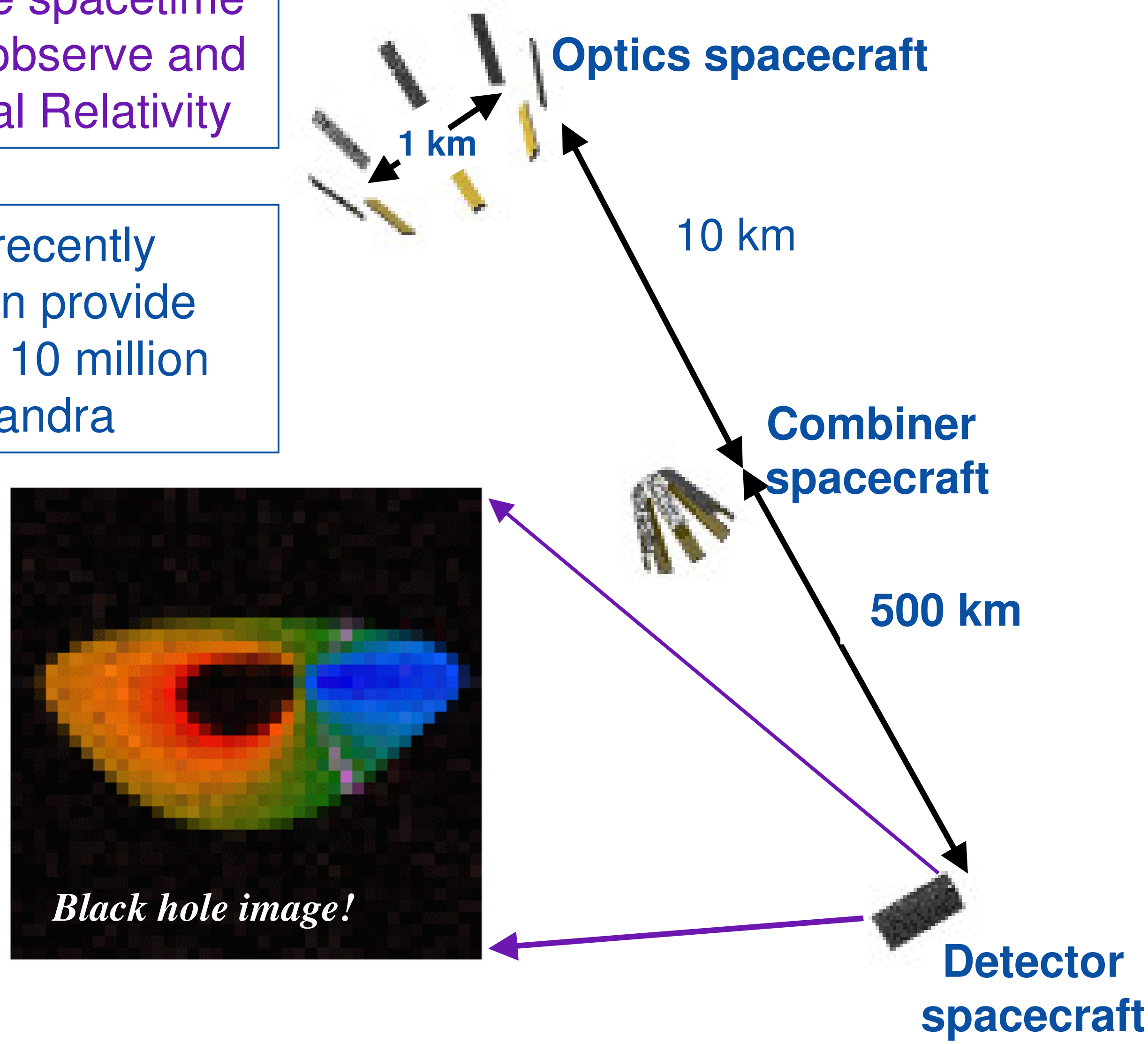


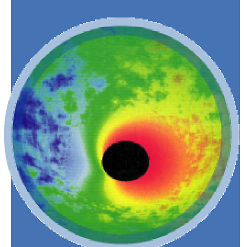
The Black Hole Imager

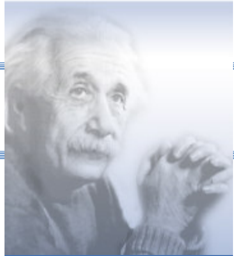
Image a black hole to map the spacetime close to the event horizon to observe and test the predictions of General Relativity

An X-ray Interferometer, recently demonstrated in the lab, can provide micro arc second resolution 10 million times increase over Chandra

Baseline of 100m to 1 km - requires formation flying multiple mirror spacecraft

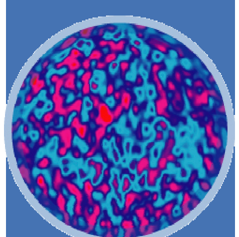


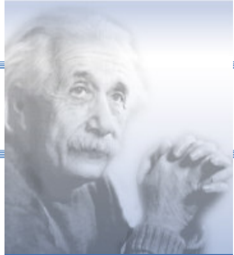




Big Bang Observatory

- Directly observe gravitational waves with sufficient sensitivity to observe the background due to gravitational waves in slow roll inflation
  - Propagating since Universe was 10^{-34} s old
  - Foreground is all binary stars and black holes in the Universe
- To separate foreground sources requires extraordinary sensitivity and angular resolution
  - Four LISA-type interferometers
  - S/C separation 50,000 km (100x smaller than LISA)
  - Peak sensitivity near 0.1 Hz
  - Strain sensitivity 1000x better than LISA
  - Inertial sensor 10x better than LISA





Objectives

I. Find out what powered the big bang

1. Search for gravitational waves from inflation and phase transitions in the Big Bang
2. Determine the size, shape, age, and energy content of the Universe

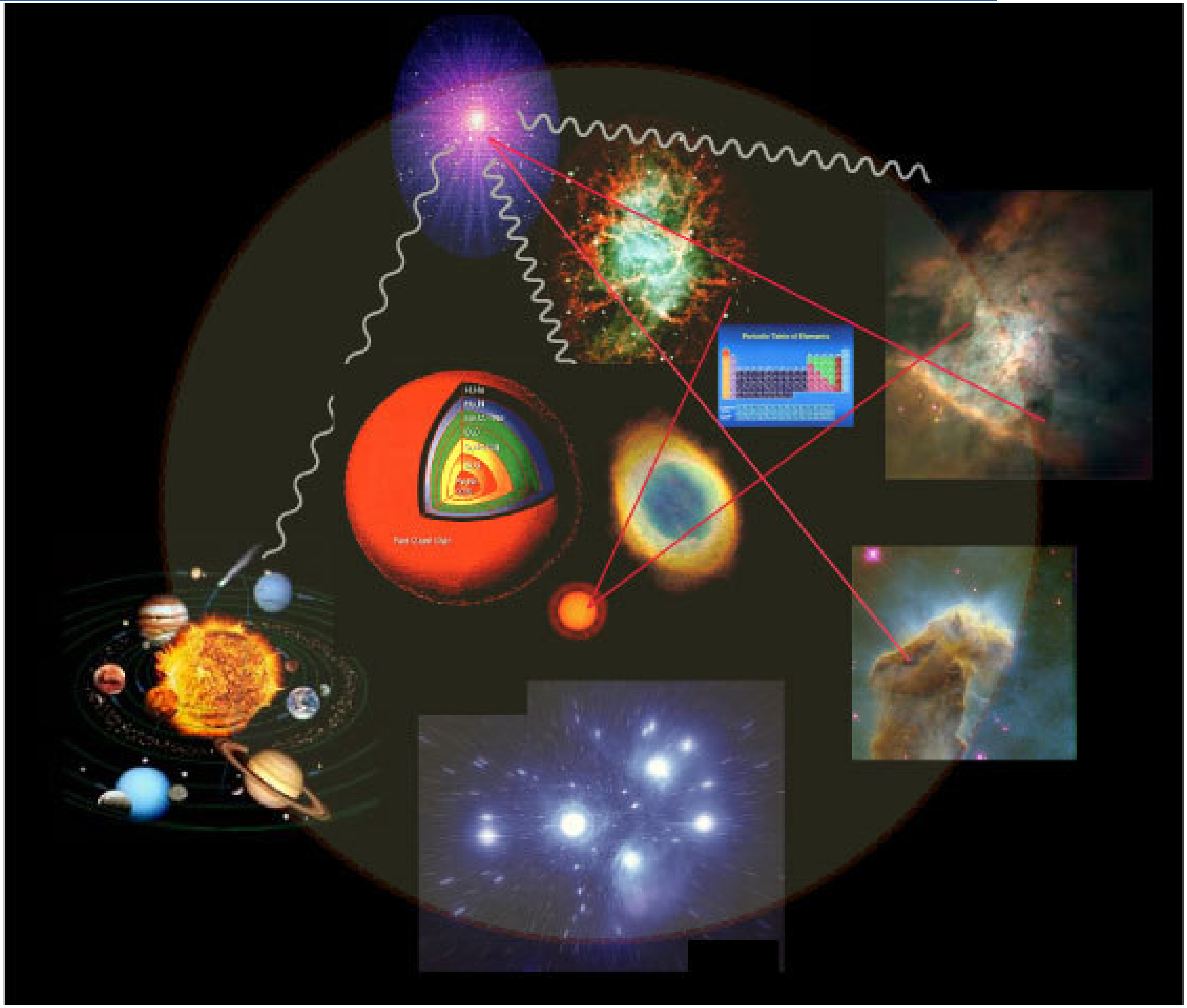
II. Observe black holes manipulate space, time, & matter

3. Perform a census of black holes throughout the Universe
4. Determine how black holes are formed and how they evolve.
5. Map spacetime throughout the Universe and near the event horizons of black holes
6. Observe stars and gas plunging into black holes

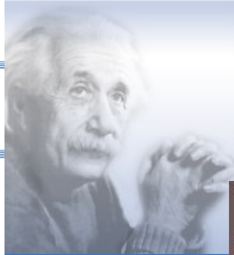
III. Identify the dark energy pulling the Universe apart

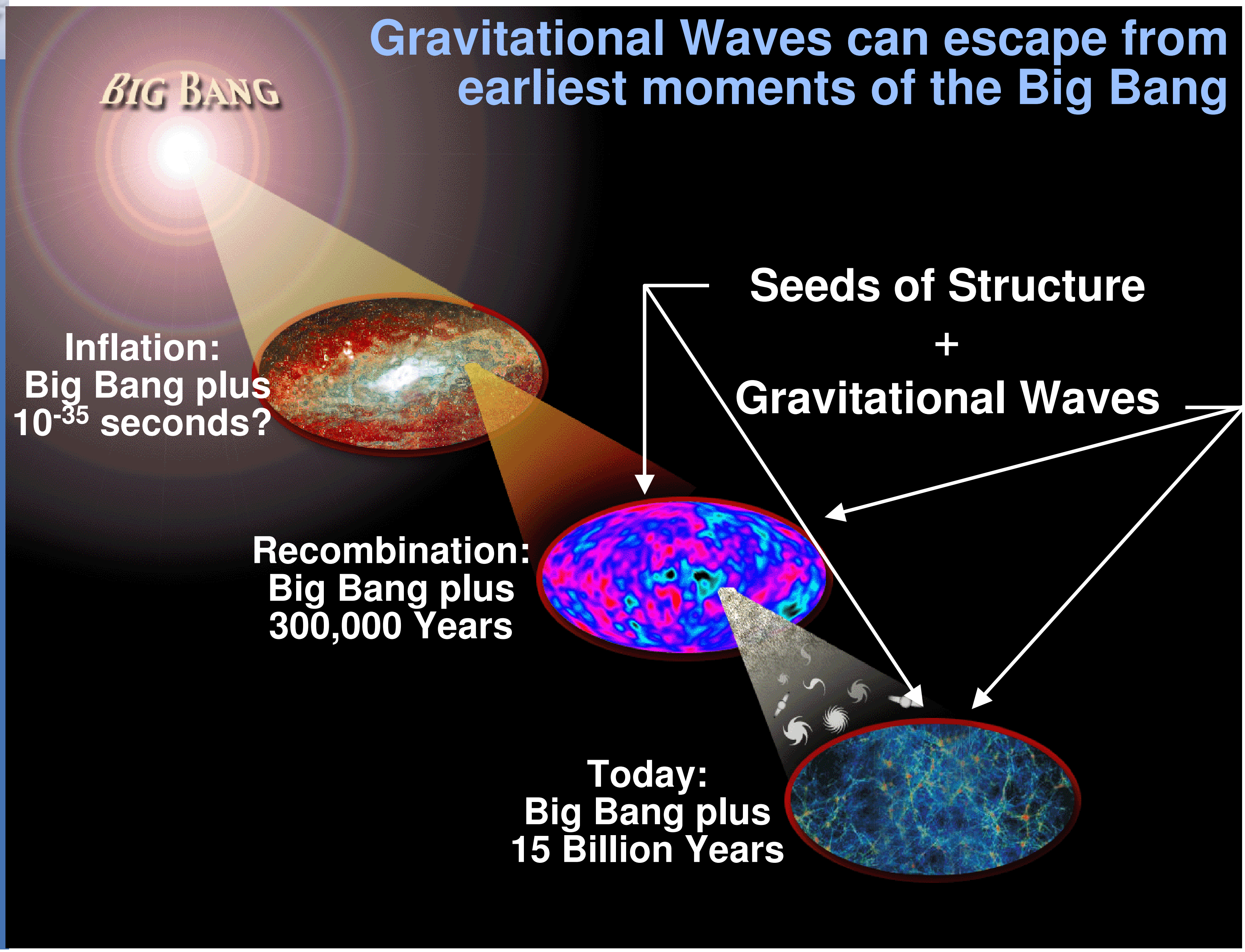
7. Determine the cosmic evolution of dark energy

Cycles



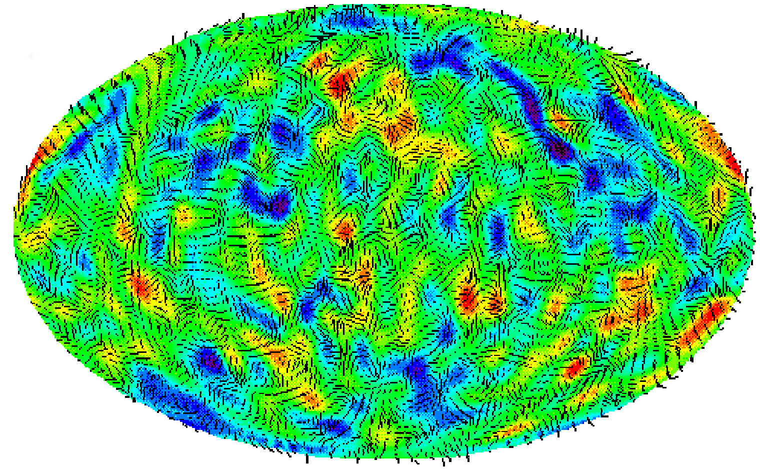
What Powered the Big Bang?

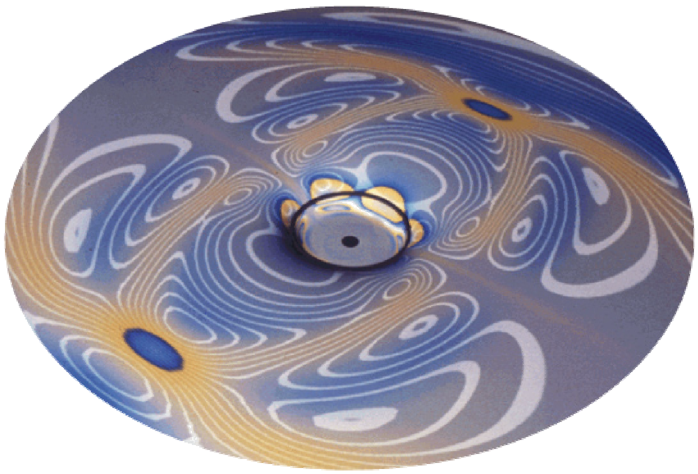




What Powered the Big Bang?

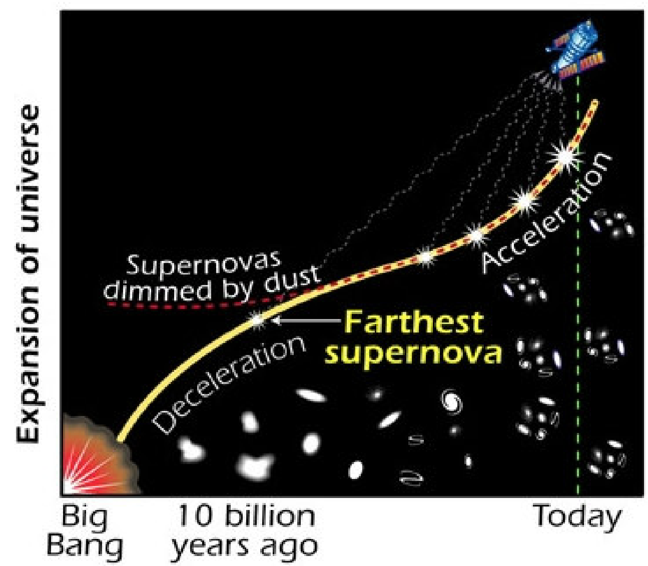
Gravitational waves leave a distinctive imprint on polarization pattern of CMB

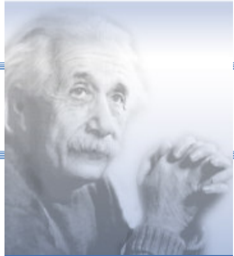




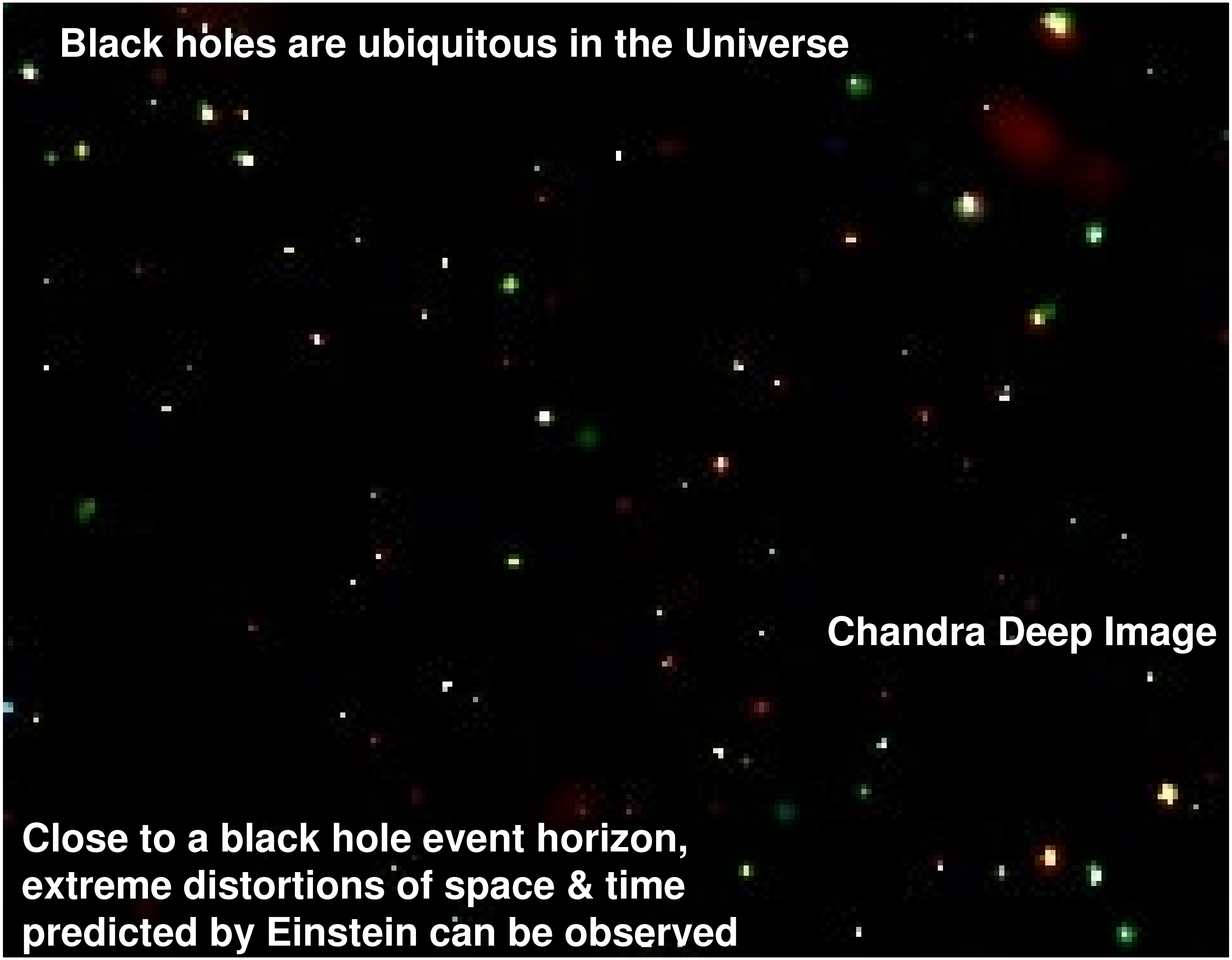
Gravitational waves from inflation and phase transitions may be detected directly

Vacuum energy powered inflation-some form of it may be the "dark energy"

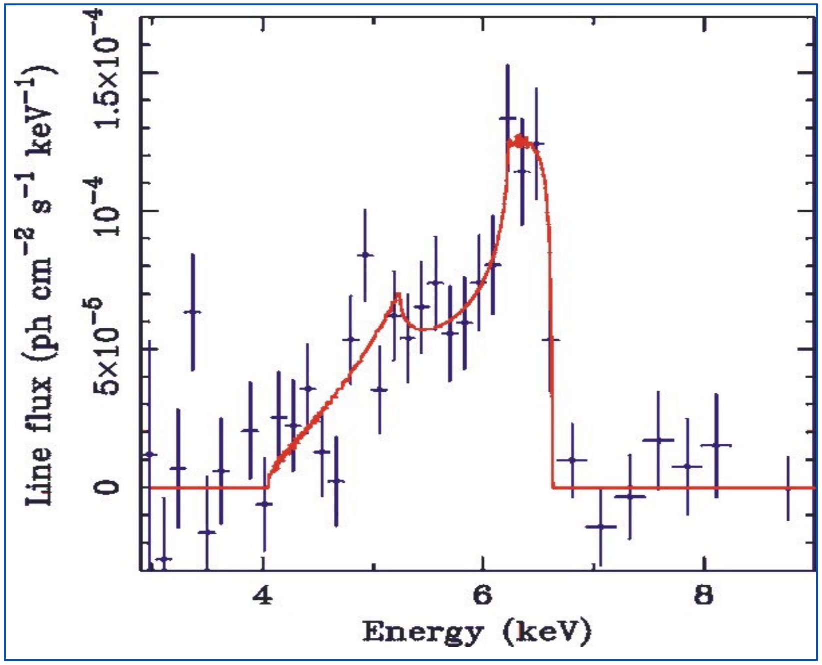




What Happens at the Edge of a Black Hole?

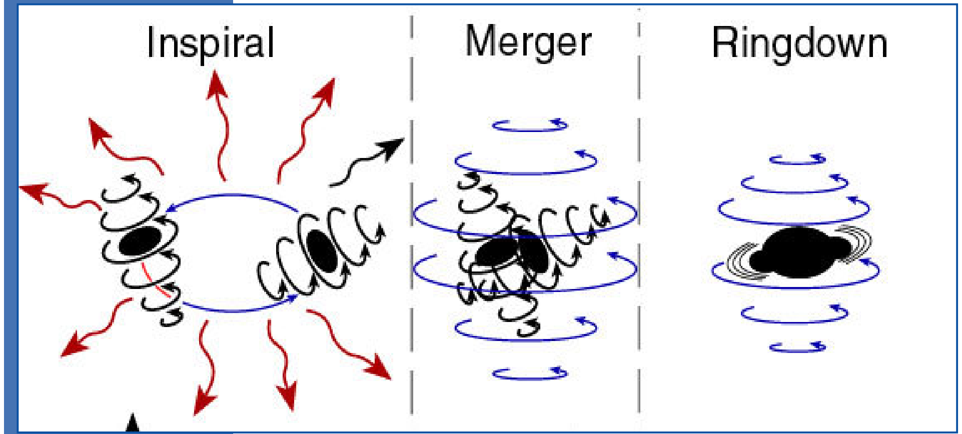


What Happens at the Edge of a Black Hole?



X-Ray Spectroscopy

- Japan-US ASCA satellite discovered iron lines near the event horizon of a black hole
- Line exhibits a strong redshift and provides a unique probe of the inner regions of black holes

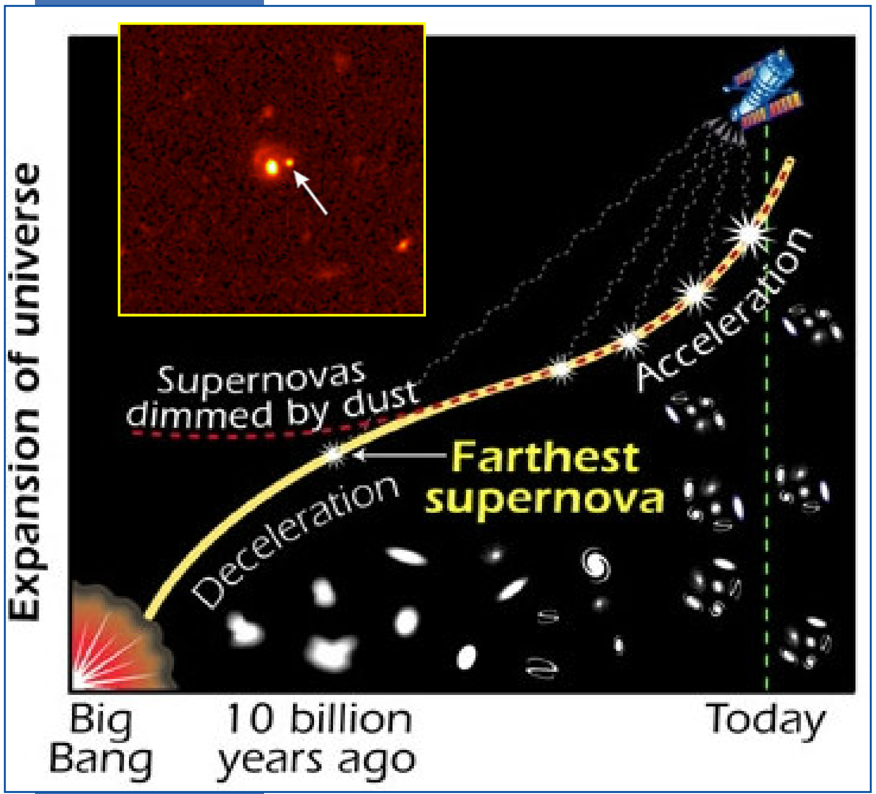


Gravitational Radiation

- Black hole binaries produce gravitational waves in all phases of their evolution
- Test of GR in all three phases

What is the Dark Energy?

Einstein introduced the Cosmological Constant to explain what was then thought to be a static Universe, "*my biggest mistake . . .* "

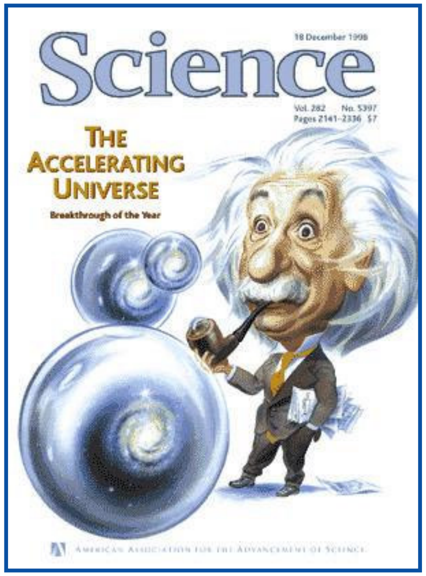


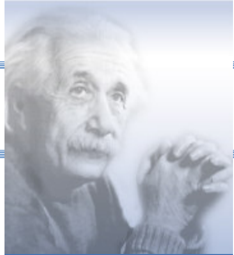
A surprising recent discovery has been the discovery that the expansion of the Universe is accelerating.

Implies the existence of *dark energy* that makes up 70% of the Universe

Dark Energy maybe related to Einstein's Cosmological Constant; its nature is a mystery.

Solving this mystery may revolutionize physics . . .





SEU Science

. . . accretion disks, Big Bang, black holes,
cosmic magnetic fields, cosmic rays, dark energy,
dark matter, extreme environments, gamma-ray bursts,
jets, large-scale structure, microwave background,
neutron stars, nucleosynthesis, relativity,
supernovae, . . .

10^{-25} cm (UHE Cosmic Rays) to 10^{15} cm (Gravitational waves)

<u>Top priority</u>: Answer the most profound questions raised, but not answered, by Einstein.

Beyond Einstein Timeline